CRYO-COOLED SAPPHIRE OSCILLATOR FOR THE CASSINI Ka-BAND EXPERIMENT*

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ABSTRACT

We present design aspects of a cryogenic sapphire oscillator which is being developed for ultra-high short term stability and low phase noise in support of the Cassini Ka-band Radio Science experiment. With cooling provided by a commercial cryocooler instead of liquid helium, this standard is designed to operate continuously for periods of a year or more. Performance targets are a stability of 3×10^{-15} (1 second $\leq \tau \leq$ 100 seconds) and a phase noise of -73dB/Hz @ 1Hz measured at 34 GHz. Test results are reported for several subsystems; including cryocooler, vibration isolation system, and ruby compensating element.

BACKGROUND

Cryogenic oscillators make possible the highest stability available today for short measuring times ($\tau \leq$ 100 seconds)[1,2,3]. However, they have so far proven impractical in applications outside the research environment due to their limited operating periods. Interruption of normal operation is typically required while a cryogen is replaced, the system then returning to nominal operation as temperatures settle down again to a stable operating condition. It is ironic that standards which are optimized for very short measuring times must operate for periods of a year or more without interruption to be considered for many applications. This is because a short-term frequency standard is typcially utilized to "clean up" the short-term variations of an atomic standard, the combined output being then distributed to various users in a facility to be used by each for their own purposes—e.g. radio science on one hand and event scheduling on another. Frequent interruption of the operation of such a timekeeping facility would be unacceptable.

Cryogenic standards also represent the best promise for improved L.O. performance as required by a new generation of passive atomic standards. These include both the Cesium Fountain and Trapped Ion standards which are under development at many laboratories around the world, and whose potential presently cannot be met using available local oscillator technologies. Because these *are* long-term frequency standards, continuous operation of the L.O. is crucial to its applicability.

Cryocoolers have been available for some time which can operate continuously for long periods of time, achieving operating temperatures as low as 7K-8K for 2 stage Gifford-McMahon (G-M) coolers and 4.2K or lower with an additional Joule-Thompson (J-T) expansion stage. However they generate vibrations which, if coupled to the high-Q electromagnetic resonator, would degrade the frequency stability. Furthermore, the J-T expansion units are relatively large and expensive, and the 2-stage G-M units show large temperature swings at a cycle frequency of a few Hz, together with a cooling capability which, while marginal at best, may degrade by as much as 1K in the course of a year's operation.

Sapphire resonators have been tested which show quality factors of $Q\approx10^9$ at temperatures up to 10K [2]. However, stable operation can only be achieved near a preferred "turnover temperature" which is typically too low (1.5K-6K) to reach with by cryocooler, and which varies from resonator to resonator depending on the concentration of incidental (~1 PPM) paramagnetic impurities. If the impurity levels could be accurately controlled in each resonator, it might be possible to construct resonators that would be compensated in the relatively narrow temperature band between that which can be achieved with available cryocooler cooling and the point at which the Q is degraded.

Sapphire resonators with external compensation have been demonstrated and proposed for high stability at much higher temperatures. A resonator with a mechanical compensation scheme has achieved stability of better than 1×10^{-13} at a temeperature above 77K[2], and combined sapphire-rutile resonators are presently under study.[4] However, the Q values of a million or so that are so far achievable with these schemes are far below those desired here.

The Q requirements for any stability value can be thought of in terms of how many times the line can be split, a

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value based on the degree of residual phase noise in the supporting electronic equipment. This number is typically about one million, with the highest value reported to date being 6 million.[2] Thus, depending on the capability of the supporting electrinics, a stability of 1×10^{-15} requires a resonator Q between 2 and 10×10^{8}.

INTRODUCTION

We are developing a cryogenic frequency standard to meet requirements of the Cassini Ka-Band Experiment. This cooperative mission between NASA and the Italian Space Agency makes use of a 34GHz link to the spacecraft to greatly reduce instabilities due to the solar plasma. During periods of the mission when the spacecraft is away from the sun, the solar plasma contribution is at a minimum, and a search for gravitational-waves will be undertaken. Later, during the orbital phase of Saturn, the rings will be examined by radio-frequency occultation.

Substantial efforts are being undertaken to increase stability and reduce phase noise for ground-based systems of the DSN, and to dramatically reduce uncertainties in (wet) tropospheric delay for the purposes of this experiment. For the two-way ranging experiments associated with the gravitational wave search, the premium is on medium-term frequency stability. The cryogenic oscillator requirement for this part of the experiment is a frequency stability 3×10^{-15} (1 second $\leq \tau \leq$ 100 seconds) and the requirement for the occulation phase is a phase noise of -73dB/Hz @ 1Hz measured at 34 GHz.

It would have been possible to install and maintain helium-cooled frequency standards for the relatively few months of operation for these experiments; however, such an approach would have done little towards improving DSN capabilities for future missions. The possibility of helium gas release and the physical logistics of cryogen replacement would result in a greater impact and risk to operation of the other frequency standards during the course of this mission, while providing an uncertain long-term benefit.

DESIGN ASPECTS

The vibrations associated with cryocooler operation present a considerable challenge to our design. However, the requirements associated with M ssbauer experiments are at least as stringent as ours, and the experimental M ssbauer community has successfully adopted a methodology that transfers heat from the experiment to cryocooler without physical contact by using turbulent convection in a gravitationally stratified helium gas.[4] A small dewar is constructed to closely fit around the cryocooler and the space between them is filled with helium gas at atmospheric pressure. This methodology, which has not previously been applied to frequency standards, allows the cryocooler and cryostat to be independently mounted from the floor. Conventional vibration reduction techniques are then applied to the cryocooler and cryostat supports.

A new 2-stage cryocooler design has recently come onto the market with capability that was previously possible only by means of an additional Joule-Thompson (J/T) expansion stage. While J/T coolers have been in use in the DSN for many years to provide cooling for the low noise ruby maser amplifiers, they are relatively large and expensive. With an ultimate temperature below 5K, the new 2-stage coolers allow a small cryogenics package, and this proven technology should provide excellent reliability.

However, thermal losses in the vibration isolation system, severe requirements on allowed temperature fluctuations, and an expected degradation of cooling capacity over the lifetime of the cryocooler all work to limit achievable temperatures. Thus even with an initial 4K-5K cooling capability, a design that calls for resonator temperature below about 8K seems risky.

This situation calls for operation of the sapphire resonator at a higher temperature than has previously been practiced in a 1×10^{-15} frequency standard. Even though quality factors of $Q \approx 10^{9}$ have been achieved at temperatures as high as 10K,[2] sapphire resonators are presently operated at a temperature turn-over point of 1.5K - 6K where the effects of thermal fluctuations are minimized, and this temperature is determined in each case by incidental concentrations of paramagnetic impurities in the sapphire.

A relatively small window of opportunity is thus defined by cryocooler capability and resonator Q which requires a resonator turn-over temperature of 8K - 10K, a fairly stringent requirement. We present a methodology that would adjust the value of the sapphire turn-over temperature by means of a proximate and thermally attached ruby element. The high chromium concentration in the ruby gives a large compensation effect that can be reduced by adjusting its position. We expect to mate each individual sapphire and ruby element in such a way to achieve a turn-over temperature of 8K - 10K.

A disadvantage of this method is that spin-dependent losses or other losses in the ruby might prevent a high Q from being achieved. This issue is discussed in the following section.

EXPERIMENTAL

Figure 1 shows a diagram of the cryogenic system. The cooling capability of the helium gas thermal transfer system was found to be only weakly dependent on the size of the gap between cryocooler and cryostat[99] and so a gap value of 4mm was chosen as large enough to prevent mechanical interference while small enough to prevent a large radiative heat influx. The area of the thermal transfer regions is found to be more important, and for this reason the low temperature station of the cryocooler was "bulked up" somewhat with attached copper conducting elements.

Overall cryogenic performance is found to be excellent. As shown in the figure, the "60K station" associated with radiation shields achieves a temperature of 57.5K, and the crucial 7K station is cooled to 5.45K with a design heat input of 0.5W into that station.

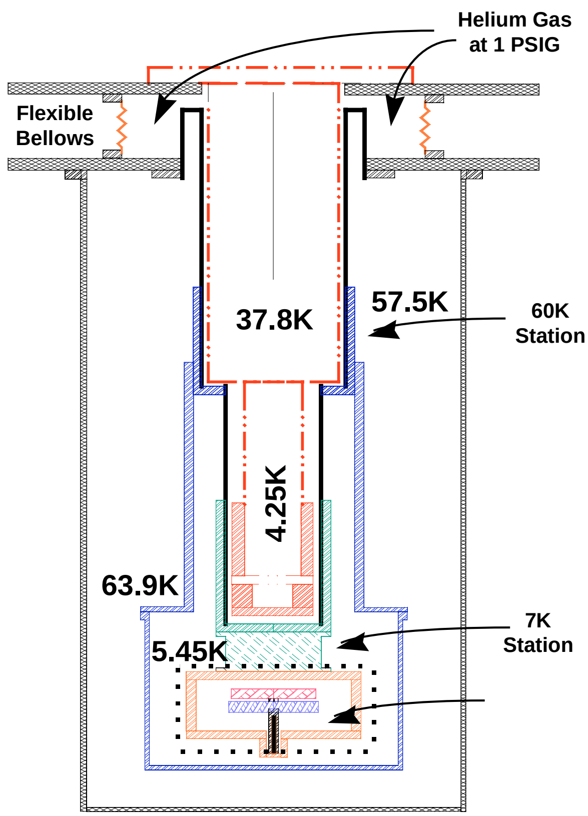

Figure 1 Schematic diagram of the cryogenic system. The cryocooler (shown in dashed lines) is independently supported from the floor, contacting the rest of the system by a flexible bellows at room temperature.

Figure 2 shows a plot of the cooling capacity measured at the 7K station. The thermal impedance of 1.69K/watt for the heat transfer system is not a bad match to the 1.27K/watt measured for the cryocooler itself. This capacity is somewhat more than needed by our design, and we might have opted for a lower capacity cooler if one had been available with the temperature performance of this one. In order to prevent helium condensation and associated helium gas management problems, a power of 0.5 watts was applied to the cryocooler. The temperature step in the graph at 0.5 watts applied power is due to turning off this added power.

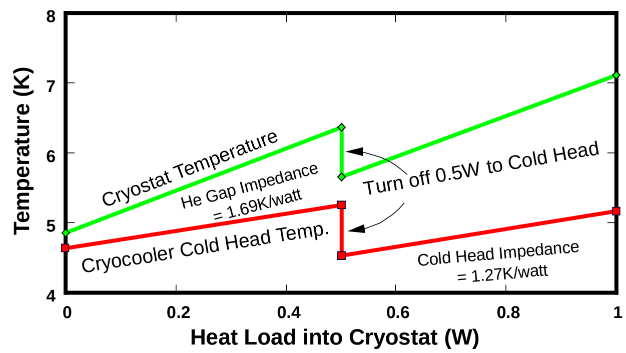

Figure 2 Response of the cryogenic system to applied heat at the 7K station (see text).

Thermal stability of the system is excellent. We had been prepared for relatively large fluctuations at the 2.5Hz cycle frequency, and had included a margin for several stages of thermal regulation. This was partly based on verbal indications from the manufacturer that the thermal variation at the cold head could be expected to be approximately 1K peak to peak. Our expectation was that they would be reduced to about 0.1K by the large thermal mass of the helium gas and had planned fairly extensive thermal regulation to further reduce the variations. We find instead that the thermal variations are only about 2mK peak to peak with 0.5 watts or less input. For reference purposes we also include as Fig. 3 the results of a measurement of cold head cooling capacity for input powers up to 4 watts.

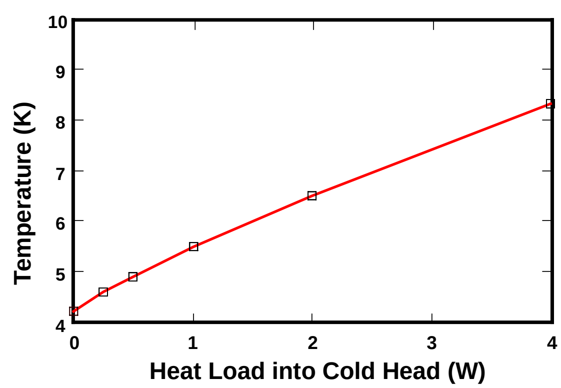

Figure 3 Measured cold head cooling capacity

Compensation of temperature-induced variation has been accomplished in sapphire resonators by paramagnetic spin[1,2] and mechanical[3] tuning effects. Such a technology is necessary to relax temperature regulation requirements. For example, compensation of sapphire's first order temperature dependence of $\approx 1\times10^{-8}$/K at 10K, leaves a quadratic coefficient of $\approx 1\times10^{-9}/(K^2)$. Thus, for 10^{-15} frequency stability, temperature regulation would need to be 0.1 μK for an uncompensated sapphire resonator compared to 1 mK for a compensated one.

While a 1 mK requirement might seem to indicate an easy thermal design task, previous experience with externally compensated resonators has shown that it is crucial to properly deal with temperature differential effects between resonator and compensator. For example, sensitivity of our (partially internally compensated) resonator's frequency to temperature without external compensation is expected to be a few parts in 10^9/K. Even with a short 0.1 second time constant for the thermal contact between ruby and sapphire, a 1mK temperature variation at the 2.5Hz cryocooler cycle frequency would be largely uncompensated. This would give an unacceptable frequency variation of parts in 10^{12} at the 2.5Hz rate.

This effect can be greatly reduced by the use of a thermal ballast. Figure 4 shows a block diagram for thermal aspects of an externally compensated resonator.

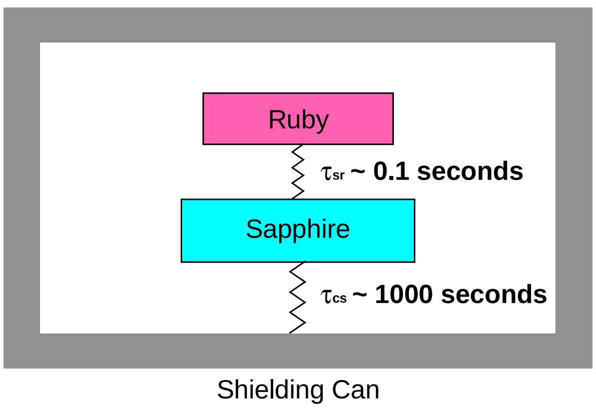

Figure 4 Block diagram for thermal aspects of compensated resonator

Even if the shielding can temperature varies, the sapphire temperature will follow only slowly, and so the ruby temperature error will be small. Adding a ballast with a 1000 second time constant provides a relieved thermal stability requirement by reducing (for times less than 1000 seconds) the differential temperature variation by 10,000 times compared to the can temperature variation. Thus, at the turnover temperature, a 1mK variation in the temperature of the shielding can will give a frequency variation of only parts in 10^{16}.

The ballast and compensator have somewhat complementary functions – without the compensator, the ballast does a fine job alone for times of 1 second or less, and without the ballast the compensator does just as well for times of 100 seconds or more.

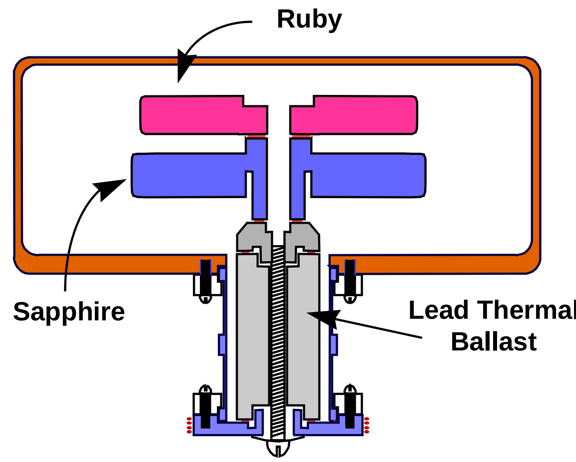

Figure 5 Compensated Sapphire Resonator. Thermally induced variations in the frequency of the sapphire resonator are canceled by paramagnetic spins in a weakly-coupled ruby element.

On the basis of measurements on recently available sapphire[99], we expect that the 1×10^{-8}/K variation at 8K-10K will be partially compensated by incidental paramagnetic spins, leaving a variation of approximately $\pm2\times10^{-9}$/K. We propose to compensate this relatively small variation by coupling a small fraction of the electromagnetic resonant energy into an ancillary ruby element containing a paramagnetic Cr spin concentration of 0.01% to 0.05%. By operating either 1 GHz above or below the zero field splitting of 11.4 GHz either sign of variation can be accommodated. Because of the difficulty and expense for obtaining the high quality sapphire resonator samples, we will characterize each sample and then adjust the coupling to the ruby element to achieve compensation in the 8K to 10K range.

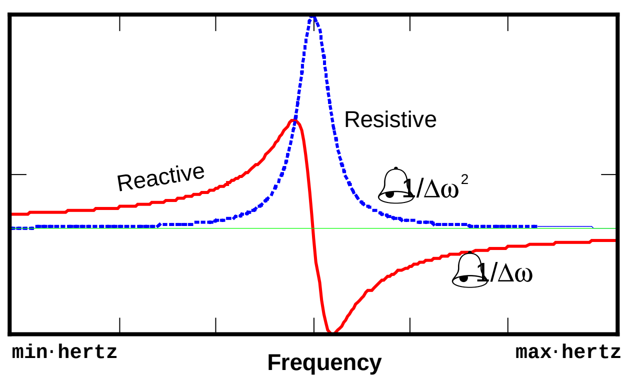

Figure 6 Resistive and reactive components for a Lorenzian absorption line

While experimental measurements of reactive and resistive components for chromium in sapphire are both consistent with a Lorenzian lineshape, we are not aware of any simultaneous measurements of the two components for the same sample. A knowledge of the ratio of these two effects in our ruby is crucial to our design, in order to know the spin limitation to resonator quality factor Q, given the required tuning rate.

The $1/\Delta\omega$ tuning dependence for incidental Cr spins in sapphire resonators has been well documented. However, the associated losses are not easy to determine at these very low concentrations, and a concern is that the linewidth may be different in ruby with its much higher Cr levels. A study done some years ago measured the spin-dependent losses in various ruby samples, finding a $1/\Delta\omega^2$ component for the losses in agreement with the expectations of a Lorenzian linewidth, but the reactive effects were not measured.[99] Combining the results of various measurements at widely varying and somewhat uncertain Cr concentration values allowed us to extrapolate a ratio between tuning and losses that was encouraging enough to proceed with our study. The ratio of tuning to loss, of course, improves for increasing values of $\Delta\omega$. We have chosen a value corresponding to Δf=1GHz as a compromise between low losses on one hand, and the requirement of a single design that will work for both signs of tuning, depending on the characteristics of any given sapphire sample.

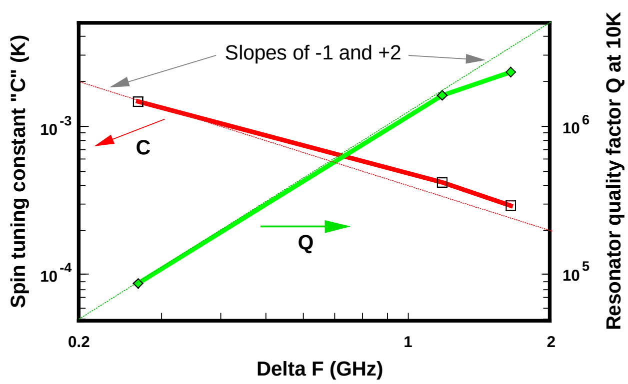

Figure 7 Measured reactive and resistive components for the permittivity of .03% Ruby sample. *Delta F* is frequency deviation from 11.44 ruby zero field splitting.

We measured the frequency and quality factor Q for 3 resonant modes of our ruby tuning element at temperatures of 6K to 15K. From these measurements we can calculate the 1/T dependent part of the frequency variation which is due to paramagnetic spin tuning, and directly infer the spin-dependent losses.

Following Mann, et al, we characterize the spin dependent part of the frequency dependence on temperature in terms of a constant C(K), where $\Delta f/f = C/T$. With aligned crystal and cylindrical axes we find, in agreement with their results, that only the WGH mode family shows a strong tuning effect. The three modes characterized in Figs. 7 and 8 are $WGE_{11,1,1}$ $WGE_{12,1,1}$ and $WGE_{14,1,1}$. As shown in Figure 7 the frequency dependencies for C and Q, are in very good agreement with predictions, linear and quadratic, respectively of a Lorenzian line shape.

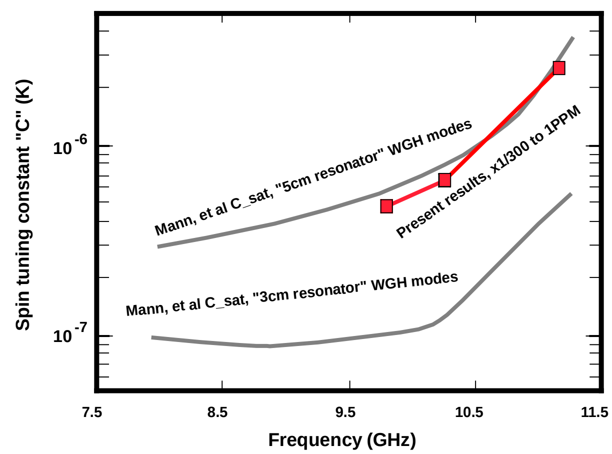

Figure 8 Frequency dependence of spin tuning for the .03% Ruby sample extrapolated to 1PPM concentration to allow comparison with previously published results.

A comparison of temperature tuning with previously reported results for incidental impurities in sapphire are shown in Figure 8.[99] Our results are consistent with a 1 PPM concentration in the “5 cm” sapphire resonator identified there.

While tuning effects are expected to be simply proportional to impurity concentration, the losses might not be. The linewidth of the ruby absorption may vary with chromium concentration. This could have meant that, for example, the losses were worse at the higher ruby concentration, and so might have prevented use of ruby as a compensating element. Our results show that, at least for the .03% ruby, this is apparently not the case.

From the data in Fig. 7 we can calculate the spin-limited Q for a resonator compensated by the .03% ruby element and operating at Δf=1GHz. These results are shown in Figure 9.

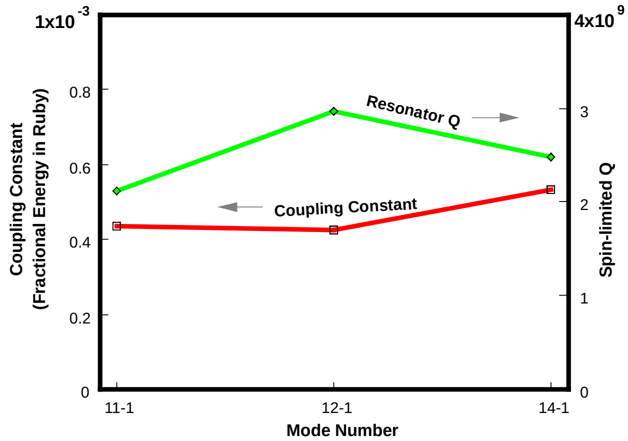

Figure 9 Required ruby coupling constants and achievable Q values for a sapphire resonator operating at 10.44 GHz and compensated at 10K.

The values are calculated using the Q and C values for each of the ruby modes independently. One might expect that the 14-1 mode, with much larger spin losses and spin tuning, would give the most accurate determination of these parameters. However, all measurements are consistent with spin-limited Q's of 2 to 3×10^9 and energy coupling to the ruby element of 0.4 to 0.5×10^{-3}. Previous experience in splitting the high-Q line in a sapphire resonator by a factor of 6×10^6 was demonstrated by an optimized Pound frequency-lock system in the 77K CSO[3]. Applied here, this capability would allow a stability of 1×10^{-15} with a Q of only 1.7×10^8.

CONCLUSIONS:

Principle design issues have been addressed for a cryocooled frequency standard to provide parts in 10^{15} short-term frequency stability for the Cassini Ka-band experiment. New cryogenic and electromagnetic design aspects have been developed to mate sapphire resonator technology to the characteristics of available cryocoolers. Several technical aspects have been verified, including cooling capability, temperature stability, and spin dependent losses in a ruby temperature-compensating element. A first unit is currently under construction and more units are scheduled to be installed in three Deep Space Network stations starting in the year 2000.

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